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Multi-target collision avoidance route planning under an ECDIS framework

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ABSTRACT

The universality of the automatic identification system (AIS) as well as the electronic chart display and information system (ECDIS) installations will provide revolutionary solution schemes for the e-navigation era of informatization, intellectualization, and integration. Based on this concept, this study adopted ECDIS as an information platform for navigational decision support and used the real-time navigation information received by the AIS to construct predicted areas of danger (PAD) for target ships. The advantages of direct viewing via the PAD in the collision avoidance give PAD a new application. Subsequently, spatial data from an electronic navigation chart (ENC) was employed as a basis for generating geographical obstacles. Through the integration of a geographic information system (GIS) module, specially designed evolutionary computation, and collision prevention regulations (COLREGS) knowledge as well as by comprehensively considering overall navigation situations, this system conducted obstacle avoidance processing and selection of a route. The system could generate a route that could simultaneously achieve multi-ship encounter collision avoidance and geographical obstacle avoidance. This is expected to provide mariners with greater convenience when working at sea, reducing their workload. This system can also be used as a reference for collision avoidance decision making.

1. Introduction

With the application of an automatic identification system (AIS) in ship collision avoidance technology, the problem of acquiring information required for collision avoidance decision-making support has been solved well. The AIS can provide static information and highly accurate dynamic information related to ships, thus offering large amounts of information and real-time data. AIS data is an important source of information that facilitate decision-making in collision avoidance. Therefore, if this automatic decision support system can be combined with the accurate and real-time navigation information provided by the AIS, it will be able to improve on the deficiencies in the previous automatic radar plotting aid (ARPA) based on predicted areas of danger (PAD). A PAD possesses the advantages of being able to intuitively, quickly, and accurately determine collision hazards, as well as to directly provide the turning magnitude to give-way. However, in the past, because of the restrictions on the characteristics of the ARPA itself, these advantages could not be manifested. Now, with the full installation of AIS equipment, we are able to solve such problems.

The electronic chart display and information system (ECDIS) is another revolutionary new technology for modern navigation after the ARPA and GPS. It connects the AIS, radar, GPS, and other navigational instruments, as well as conducts comprehensive processing and display of real-time information of various forms of navigation. Thus, it has significant effects on ensuring navigation safety and improving navigation operating efficiency. It can be said to be an information center of navigation. This is an essential platform for constructing a collision-avoidance decision support system.

Planning an optimal collision avoidance route includes not only the most important aspect of navigation safety, but also economic factors and other many aspects. As it is a multi-criteria, nonlinear programming problem, we require an optimized processing method with greater flexibility and efficiency. Evolutionary computation has great potential for dealing with this kind of problem.

Therefore, by combining the accurate information of the AIS, the intuitive collision avoidance information of the PAD, the processing ability of a geographic information system (GIS) for spatial data of obstacles from an electronic navigation chart (ENC), the flexibility of evolutionary computation for route design, and the specifications of a collision prevention regulations (COLREGS) knowledge, as well as the ECDIS platform for processing, analysis, and integration of data, this study attempted to carry out a comprehensive evaluation, from monitoring the overall water navigation situations to automatically planning an optimal route that can simultaneously conduct multi-ship encounter collision

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avoidance and multi-fixed-obstacle avoidance. This aims to provide a mariner with greater convenience when working at sea, reducing their workload. It can also be used as a reference for collision avoidance decision making.

2. Previous work

On the topic of collision/obstacle avoidance route studies, quite a number of papers have been presented (Tam et al., 2009). Iijima and Hagiwara (1991) developed a set of knowledge-based expert systems for determining collision risk, decision making for planning collision avoidance, and manoeuver control. Churkin and Zhukov (1998) used continuous and discrete mathematical models with linear planning methods to solve a manoeuver path for obstacle avoidance. Hwang (2002); Kao et al. (2007); Su et al. (2012) used fuzzy set theory to assess the risk of collision and determine a maneuver route for collision avoidance. Liu and Shi (2005) used neural networks and fuzzy set theory to assess the most threatening target ship and generate a corresponding collision-avoidance maneuver action in accordance with COLREGS, encounter forms, and the speed ratio and bearing of the ship. Tam and Bucknall (2013) effectively solved for an optimal collision avoidance path under in a multi-ship encounter situation, in accordance with the COLREGS knowledge base, the maneuvering characteristics of the ships, and the ship motion equations, but this study assumed that data on the mechanical properties and hydrodynamic characteristics (propulsion, resistance, radius of gyration, and stopping distance) of all the ships are known.

In recent years, heuristic approaches have also been receiving increased attention from scholars (Ito et al., 1999; Smierzchalski, 1999; Szlapczynski, 2009, 2011; Szlapczynski and Szlapczynska, 2012; Tam and Bucknall, 2010), owing to their more flexible design method. A heuristic approach only searches a partial space that is more likely to yield solutions. It is a stochastic optimization technique. Its solution can produce a near optimal solution, rather than the overall optimal solution. Because of such properties, both the iteration time and frequency are shorter.

From the above literature review, we can deduce the parts that can be strengthened, which are the areas for improvement in this study:

a. Some studies only consider two-ship encounters, but cannot be applied to optimal collision-avoidance path planning in multi-ship encounters. Some studies on methods for processing multi-ship encounters turn a multi-ship encounter into a series of two-ship encounter problems to process, which lacks a consideration of the overall navigation conditions.
b. The inability to incorporate COLREGS into the principles of path planning results in a collision avoidance path being planned that does not comply with nautical practices.
c. Using point objects to represent the own ship or target ships does not take into consideration the characteristics of a ship domain which may exist.
d. Studies that only consider dynamic obstacles (ships) without considering fixed obstacles (islands and reefs) can only be applied in open seas, and cannot be applied in restricted waters.
e. Without considering integration with an ECDIS and AIS. Thus, both the performance and efficiency can be further upgraded so that the system can then meet the navigation decision-making needs of the future.
f. When performing evolutionary computation, most of the first-generation ethnic group is randomly generated, and its quality will greatly affect the subsequent fitness and convergence rate.

3. Integration of the AIS and ECDIS for the collision-avoidance route-planning platform

Encounter information in the AIS system can be accessed in nearly real time, prompting a PAD to obtain nearly real-time updates to facilitate determining changes to collision hazards. This has changed the PAD-type ARPA, which was previously only applicable and restricted to open seas navigation, but can now be intuitively applied to narrow waterways that have a density of vessels. This study focuses on the foundation of AIS and ECDIS integration by using the target vessel position and course information acquired from the AIS and GPS position of the own ship to calculate the basic parameters required for collision avoidance, such as bearing, distance, distance at closest point of approach (DCPA), and time to closest point of approach (TCPA). Thus, the required target ship PAD is generated, displayed, and integrated in the ECDIS in order to be basis data for further collision-avoidance route planning.

The AIS system provides the longitude and latitude of the vessel's position, and the speed over ground (SOG) and course over ground (COG) for the target ship. Therefore, there is no need to recalculate the course and speed of a target ship. However, when calculating the position of a target ship relative to the position of the own ship, there is still need to convert the bearings and distances to calculate the DCPA and TCPA.

As shown in Fig. 1, it is assumed that the position of the own ship is O (L_o, λ_o); the position of the target ship is A (L_t, λ_t); the SOG and COG of the own ship and the target ship are, respectively, V_o and C_o and V_t and C_t. The two-ship relative motion velocity is V_r. Based on this information, the own ship is taken as the origin. To establish a coordinate system, the X-axis facing upward denotes north with a true azimuth of 000°, and the Y-axis is perpendicular to the X-axis to the east with an azimuth of 090°.

The DCPA is given by

$$\mathrm{DCPA} = d \times \sin(C_r - B_0) \quad (1)$$

The distance between the two ships is d. C_r is the bearing of the target ship. The bearing of the target ship observing the own ship is $B_0 = B + 180°$, if $B_0 > 360°$, then $B_0 = B_0 - 360°$. The two-ship relative motion direction is B.

When the DCPA value is positive, the target ship will pass through the stern of the own ship. When the DCPA value is negative, the target ship will pass through the bow of the own ship. The TCPA is given by

$$\mathrm{TCPA} = |d \cdot \cos(C_r - B_0)| / V_r. \quad (2)$$

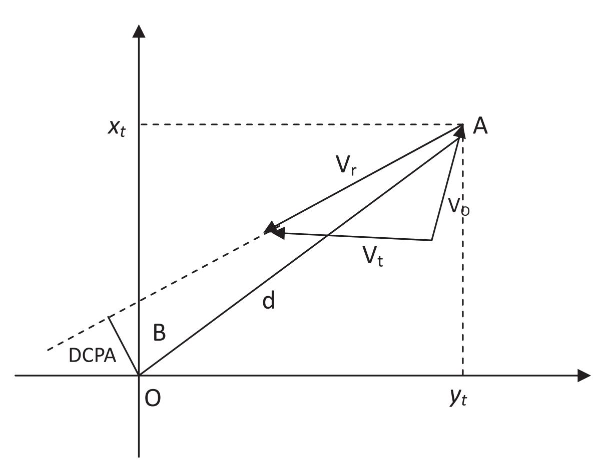

Fig. 1. Analysis of AIS encounter information.

4. Integration applications of the PAD on ship collision avoidance

The application of a PAD first appeared in the SPERRY ARPA series. When used in collision avoidance, it changes the ARPA radar from predicting a dangerous "point" to predicting a dangerous "area". Compared with the vector-type ARPA, the PAD-type ARPA provides more intuitive collision avoidance information. However, nowadays PADs are not installed in any ARPA radar device, and so are not in use. PADs require some understanding of the principles, and a misunderstanding of the data can lead to greater danger. Since a PAD is established on the basis of information obtained by an ARPA radar device, the limitations related to the ARPA radar itself in accessing information will affect the generation of the PAD (such as blind spots, waves, rain and snow interference). When the error in radar information is larger, the boundary errors of a PAD are equally obvious. Furthermore, as a prerequisite of establishing a PAD, the own ship must maintain a constant speed and the target ship must maintain a constant speed and course. In the actual encounter, to avoid a collision, the two ships could take their respective actions, but the PAD information must receive real-time updates. However, for the ARPA radar to reach stable tracking on the target for displaying sufficiently reliable information, about 1–3 min time is required; this will result in delays in the generation of the PAD. Hence, the information obtained from the PAD cannot be completely used to determine collision hazard. Moreover, in case of a multi-ship encounter, the radar screen will be overly complicated, increasing the complexity of interpretation. However, through the combination with ECDIS and integration of AIS information, such a situation can be improved. The real-time information required to calculate the PAD can be obtained from the AIS, and the calculation and generation of the PAD can be conducted on the ECDIS. The ECDIS screen can simultaneously display the chart information and the PAD collision avoidance information of target ships.

Fig. 2 shows a geometric mapping of a ship's PAD. In the mapping, the own ship is positioned at point O with a velocity vector V_O; the target ship is positioned at point T with a velocity vector V_T. The TO straight line is the line of relative movement where the two ships exactly collide ($DCPA = OD_1$). The TD_1 and TD_2 straight lines are, respectively, the lines of relative movement where the target ship takes the own ship's preset DCPA through the own ship's bow and stern. Assuming that the target ship maintains its course and speed, and the own ship maintains its speed, we can determine the PAD on the target ship's course line. In the mapping process, T_1 is taken as the center of a circle ($TT_1 = V_T$), VO is the radius of a drawn arc, intersecting with TD_1, TO, and TD_2 at the A_1, A, and A_2 points, respectively.

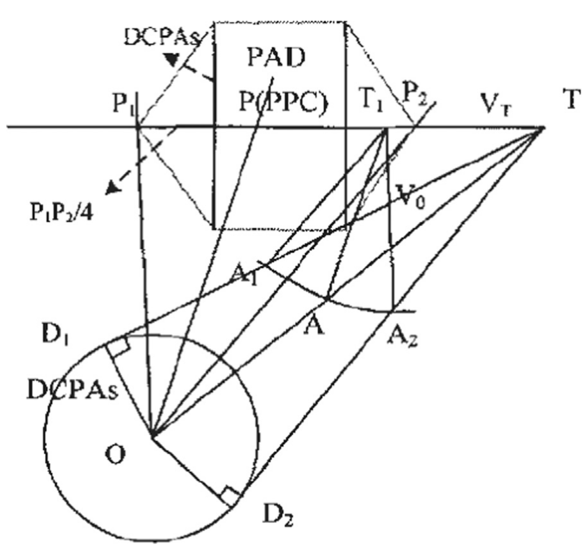

Fig. 2. Key principles of the PAD.

This indicates that when the own ship adopts the AT course, then the own ship's course line will intersect with the geometric collision avoidance line of the target ship at point P, which is the predicted point of collision (PPC). When the own ship adopts A_1T_1 or A_2T_1, the own ship's course line will intersect with the target ship's course lines at points P_1 and P_2, which are the two vertices of the PAD; then we can create the PAD at these points. The own ship's bow line passing through points P_1 or P_2 indicates that the target ship will pass by the own ship with a safe DCPA. When the own ship's course line intersects with the PAD, it indicates that the target ship cannot pass by the own ship with a safe DCPA.

The OOW can use the electronic bearing line to plot the dangerous course range of the own ship and obtain the corresponding magnitude of the turning to give-way. Without going through the method of a trial maneuver, the OOW can obtain the angle of turning, reducing the time taken for collision avoidance decision making. During a multi-ship encounter, the OOW can still refer to the shape of each vessel's PAD and their positions, visually determine the most dangerous ship vessel, and then make the correct decisions for collision avoidance.

5. Application of the GIS in collision-avoidance route planning

5.1. GIS processing on fixed/non-fixed obstacles

Route planning is one of the most important functions of the ECDIS, and the methods to achieve it are mostly related to the GIS. The GIS is a very important module for processing spatial data in the ECDIS, especially for the aspects of pre-processing related to spatial data, route planning, and route checking. In this study, the GIS module plays a role in the following:

5.1.1. Spatial data pre-processing

The route itself is a linear spatial object, while the spatial data related to navigation is constructed from three types of basic spatial data structures: point, line, and polygon. Thus, the processing and analysis involved are exactly the interactive operations between these three basic objects:

(1) Point objects can include isolated reefs, wrecks, navigational aids, etc. They have a certain range of affect; usually, a route will avoid them.
(2) Line objects include dangerous contour line, undersea cables, etc. They also have a certain range of affect. Usually, a route will avoid them and try as much as possible to avoid crossing them.
(3) Polygonal objects have many types and include boundaries of obstacles and the borders of other natural and cultural areas. They also have a certain range of affect. Usually, the route will avoid them, and try as much as to avoid crossing over them. We also classify the hexagonal PAD of a dynamic ship in this category.

From the above, it is implied that each type of spatial objects and its range of effect will influence route planning. Therefore, we must set the affected buffer zones on each spatial object by enlarging all of the spatial objects as polygons (Fig. 3). The buffer zone size is a parameter that can be adjusted by the user based on different objects and aims. This function is a basic function of the GIS. As this study used the GIS as the platform, the buffer zone was directly generated by the GIS. Therefore, all the obstacles and the

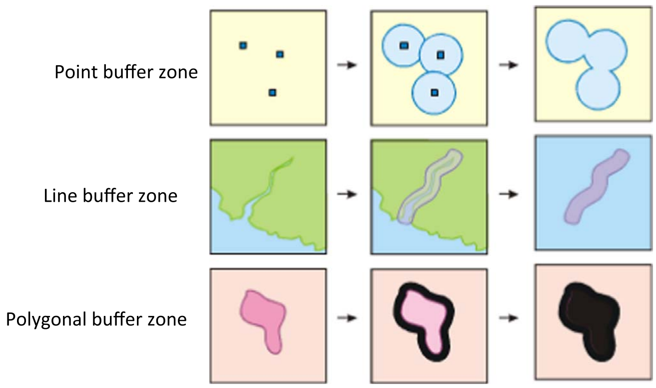

Fig. 3. Buffer zones of individual spatial objects (Tsou, 2010).

target ship's PADs in this study were treated as polygons so that they can be processed with the method used for polygonal obstacles. The process is simple and the results are of high quality.

5.1.2. Spatial data analysis

After determining the buffer zone and polygon of each spatial object, we then need to re-apply the intersection function in the GIS to conduct the test. Through the intersection tests on routes and obstacles, we can determine which spatial objects intersect with this route, the intersection point, and the length of intersection, thereby determining whether the route is feasible and how to plan collision avoidance.

5.2. Establishment of initial routes

From the literature review, we saw that most of the studies generated a set of initial routes through a random method, and thus they contained many poor-quality individuals (such as routes that violate the collision avoidance rules or cross over obstacles). This type of set of initial routes will indeed affect the fitness of individuals in the iteration process as well as the speed of iteration.

The previous section described using the GIS to conduct preprocessing of spatial data. After generating this value-added data, some of the spatial geometric computing functions provided by the GIS are then initiated to perform automatic generation of candidate routes. These higher-quality candidate routes help to carry out the subsequent selection of routes. The method of establishing these higher-quality candidate routes is to employ the algorithms of Tsou (2010). As shown in Fig. 4, when a ship needs to sail from the starting point of S to the destination point of P, the process of generating candidate routes is as follows:

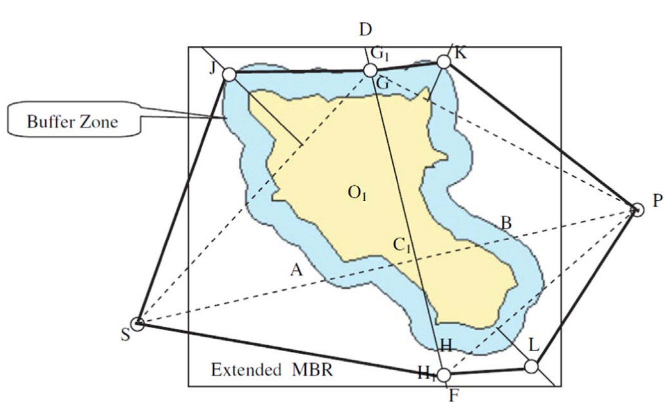

Fig. 4. Schematic diagram of initial obstacle-avoidance route generation (Tsou, 2010).

a. First, establish a test line SP from S to P. If the test line does not go through the obstacle area, then the ship can navigate linearly between the two points. If only considering the maritime requirements, then the straight line segment from S to P is the shortest navigation line segment on the chart.
b. If the line SP goes through the obstacle area, then a polygon O_1 that intersects with the test line and is nearest to the S point will be derived. Assuming that the test line SP and O_1 intersect, the two points closest to the S point are points A and B, and the midpoint of the line segment AB is C_1. Next, we establish a straight line through C_1 perpendicular to the AB line segment, and with the minimum bounding rectangles (MBR) intersecting at D and F, we re-intersect with O_1 at G and H.
c. Take a random point each from the DG line segment and the HF line segment as G_1 and H_1, respectively. These two points cannot fall into other obstacle areas. Next, respectively re-establish the SG_1 and SH_1 line segments from point S to G_1 and H_1. These two line segments are the two possible navigation lines through the two sides of the obstacle area. However, if part of the boundary of O_1 is displayed outside the assigned range on the map, then only one side of the route will be calculated within the display range; or, if this obstacle area has been divided into two routes, then only one side will be tested, and the other side can be ignored.
d. Take G_1 and H_1 separately as the assumed endpoints. Conduct a dichotomous cut of the line segments constantly and recursively. Repeat the test steps (b) and (c) to obtain the waypoint of J. Then, the SJG1 line segments and the SH1 line segment are the waypoint and routes, respectively, of the first half, passing by this obstacle area.
e. Again, take G_1 and H_1 separately as the starting points, and P as the endpoint. Likewise, conduct a dichotomous cut of the line segments constantly and recursively. Repeat the test steps (b) and (c) to obtain the waypoints of K and L. Then, the G1KP line segments and the H1LP line segments are the routes and waypoints, respectively, of the second half, passing by this obstacle area.
f. When the generated routes do not intersect with the current obstacle area, this means that the bypass of this obstacle area has been completed. After connecting each waypoint, the two routes of SJG1KP and SH1LP can be obtained.
g. Conduct generalization processing for the generated routes to remove excessive waypoints.
h. To perform evolutionary computation on the assigned set of initial routes, assume that the initial number of lines is *n*. The system will be based on this setting to repeatedly execute the previous six steps.

The routes established by the above method are neither the shortest routes nor the optimal routes, but these lines can provide a reference for evolutionary computation to establish an initial set of routes when searching for the optimal route and they can be used as a basis during evolution.

6. Evolutionary computation for selection of collision-avoidance route planning

Evolutionary computation is a type of global and random optimization algorithm based on natural selection and natural genetics. From the viewpoint of genetics, it is an analogy to Darwin's evolutionary perspective of natural selection, that is, the survival of the fittest in nature (Back, 1996). In the field of problem solving, a random search of a whole domain in parallel prompts the population expressing the problem-solving process to evolve towards a global optimal solution, which implicitly has the characteristics of a parallel algorithm. The genetic algorithms perform the same steps of reproduction, selection, crossover, mutation, and so on in the evolutionary process of each generation. Since it has fewer restrictions on the fitness function and constraint conditions, and the search scope is throughout the independent variable space, it has the larger probabilities towards a global optimal solution through the iterations. It can effectively solve real-world complex nonlinear optimization problems.

This study focused on several important aspects of evolutionary computation, including gene coding, design of the fitness function, manipulation of reproduction, manipulation of selection, manipulation of crossover, manipulation of mutation operations, and the selection of control parameters. These are to be suitably applied to the improvement of route planning, so that it possesses the ability to process multi-criteria selection of route planning. Furthermore, the candidate route generated by evolutionary computation considers only the shortest distance, which may not be in line with navigation practice. Therefore, we inserted the collision avoidance regulations for ship-to-ship in the COLREGS (Rules 13, 14 and 15) into the generation, elimination, and selection processes of the candidate route, as the principles of collision avoidance during an encounter with a non-fixed obstacle (the target ship).

6.1. Gene coding for routes

A series of waypoint nodes is used to represent a route. Each waypoint node is equivalent to a gene. The chromosome constructed by combinations of these genes (waypoints) is equivalent to a route. To express this arrangement, the number of waypoint nodes of each route is different, and this is the biggest difference with the fixed number waypoints of the linear programming approach and it has the benefits of more flexibility. Each waypoint node records the longitude and latitude coordinates of the waypoint. This approach allows ease of calculation and manipulation, introduces professional maritime knowledge, and reduces the complexity of gene encoding and decoding, as well as improve the efficiency of computation.

6.2. Evolution operations

6.2.1. Fitness function for route elimination and selection
A fitness function is a function representing the survivability of an individual in a competition. It is a function to be optimized. Generally speaking, route planning must be able to meet many constraint conditions; it is a type of multi-criteria optimization problem. However, since this study is focusing on the signal receiving range that can be attained by the AIS, the distance is typically not very far away (within 30 nautical miles) and the environment is relatively simple and less affected by hydrographic conditions. Impassable routes that cut across the obstacle area (artificial or natural) have been filtered out, so only the shortest total distance is pursued in the design of the fitness function. Other criteria are temporarily retained and will be incorporated when needed.

6.2.2. Elimination of routes operation
When assessing suitability, in order to preserve the elite individuals and accelerate the convergence of operations, the elite preservation strategy is adopted. The finest elite individuals in the contemporary ethnic groups do not participate in the elimination, mutation, and crossover manipulations, in order to be directly copied to the next generation. For the remaining individuals, each individual in the ethnic group is assigned a sorting number, based on their fitness values in descending order from highest to lowest. The sorting numbers are directly used to carry out selection. The selection is then performed using the roulette wheel selection.

6.2.3. Genetic operations for routes (Fig. 5)
6.2.3.1. Crossover operation. Adopting the randomized single-point crossover approach, the crossover randomly selects a waypoint sequence to divide the two chromosomes (routes) into two parts, and then combine the first half of the first chromosome with the second half of the second chromosome, while the remaining parts are also re-combined, generating two new chromosomes (routes). However, it must ensure that the new generated routes do not cut across the obstacle area.

6.2.3.2. Mutation operations. These include:

(1) Perturbation operations: After specifying the range of the perturbation, the coordinates of a certain node in the route are randomly changed, so that the coordinates after perturbation cannot exceed this range.
(2) Node-adding operation: In between the adjacent two nodes, taking the middle point of this line segment as the center of a circle and half of the length of the line segment as the radius, a new node is added and situated within this circular range.
(3) Node-removing operation: A certain node in the route is randomly removed, but the starting point, endpoint, and points of specified area cannot be removed.

All operations above must ensure that the routes will not cut across obstacles after the mutations. Through appropriate mutation operations, the quality of a new route can be ensured and it will not deteriorate, preventing the fitness value from falling into the local optimal solution.

6.3. Fitness function of route elimination and selection

Fitness function is the function representing the survivability of an individual in a competition; it is generally a function used in conducting optimization. Since the impassable routes passing through the obstacle zone (artificial or natural) are filtered out in advance, in this study, evaluation is performed only on the length of the voyage. The target function is established as follows:

$$F = \min f_1'. \tag{3}$$

In this study, we consider $f'_1 = (f_1 - \min f_1)/(\max f_1 - \min f_1)$, where f_1 is the total number of voyages, which can be derived by summing up the distance values between the nodes; f'_1 is the cost value of passing through after normalization; the lower this value, the better it is.

7. Simulation results and discussion

The simulation has been validated using several standard and complex traffic scenarios. These tests are primarily to evaluate the output's compatibility with COLREGS as well as its practicality and consistency. Regarding the settings of the simulation environment, the simulation range is similar to the receiving range of a typical AIS (about 30 km × 20 km), including islands, reefs, and other fixed obstacles. In the display, these obstacles all have the buffer zones included, represented by polygons. The target ship's data comes from the received data of the AIS and is expressed with a hexagonal PAD; hence, all obstacles for collision avoidance are represented by polygons. We assume that the own ship's speed is constant, the target ship maintains a fixed course and speed, and the own ship only relies on changing its course to perform collision avoidance; such approaches are consistent with the general practices of navigation. Nevertheless, when a new target ship is detected, the target ship changes course or speed, or even the own ship changes speed, there is a need to conduct another simulation. Regarding the settings for the selection of routes, immediacy is a more important requirement for the avoidance of collisions between ships. If the selected group size is too large, although it facilitates the search for the optimal collision-avoidance path, the search time will increase, which is not conducive to real-time decision support. Because this study generated the initial routes via the GIS, the quality is better than that of the random generator, and therefore the initial number of ethnic groups can be much smaller, and the convergence rate is also faster.

After a comprehensive consideration of the specific situations of ship collision avoidance, and fine-tuning the tests through simulations, the parameters of the evolutionary computation were set as: a group size of 30 (or even 10 would be sufficient to achieve an acceptable outcome); a crossover rate of 0.6; and a mutation rate of 0.04. After applying the genetic manipulations above to produce offspring to replace the parent, when the optimal fitness value achieves convergence, or after it reaches the required evolution generations the search will be terminated, indicating that the optimal route has been found.

Below, we present three types of encounter situations with empirical descriptions. In the figures showing the simulation results, the black arrow with the blue line represents the own ship with a straight path between the start and end points; the red arrow with the red line and the green arrow with the green line, respectively, represent the assigned routes of the target ship as a stand-on vessel and as a give-way vessel. The brown bold line denote the assigned route for predetermined traveling of the own ship. It may be a straight path or a recommended route. The remaining fine lines are candidate routes in the execution process of evolutionary computation. Each ship follows the assigned route and travels along it. The area between the routes may pose risks of collisions. The red circle denotes the guard ring of the own ship. The radius of this ring is the assigned DCPA value (1.5 nautical miles in this study). The execution time depends on the number of obstacles. Generally, it can be completed within 5 s, and in not more than 10 s in a more complex environment (Fig. 5).

7.1. Case I (general crossing situation)

This simulation includes static obstacles and a dynamic obstacle. The route must be able to avoid these two types of obstacles at the same time. The own ship has a course at 065° and a speed of 15 knots. The target ship's data is tabulated in Table 1. Fig. 6 shows a case of candidate routes randomly generated by evolutionary computation without GIS pre-processing. From the diagram, we can see that the candidate routes with a sailing value are very few. Fig. 7 shows the navigation situation after integrating the GIS pre-processing. We see that the quality of candidate routes is significantly better than the routes randomly generated. Under such a navigation situation, if the own ship maintains the original course and speed while no action is taken, the TCPA will be 22 min and the DCPA will be 0.3 nautical miles. Therefore, there will be risk of a navigation collision (Fig. 8). According to the provisions of Rule 15 in the COLREGS, the own ship is a give-way vessel. It should turn right to give way to the target ship, and the turning angle should be large and obvious. After the simulation, the target ship's PAD is generated and a new route is proposed to turn right. The route avoids the PAD and also avoids the islands and reefs (Fig. 9). During the simulation, the own ship remains outside the PAD to ensure it has an adequate DCPA. When the simulation time reached 24 min, the own ship just cut to the edge of the PAD, but still maintained the assigned value of the DCPA and successfully avoided the obstacles (Fig. 10).

Table 1
Case I – target ship's data in a general crossing situation.

Course	Speed	Bearing	Distance	DCPA	TCPA
309°	10 kts	089°	8.6′	0.3′	22 min

7.2. Case II (head-on and overtaking situations)

This simulation contains both a head-on vessel and an overtaken vessel. The own ship is the overtaking vessel with a course of 288.6° and a speed of 9 knots. The target ship's data is tabulated in Table 2. Fig. 11 shows the situation. If the own ship maintains the original course and speed while no action is taken, the TCPA with target A and target B will be, respectively, 112 min and 56 min. There will be risks of navigation collisions with both targets. According to the provisions of Rule 13 in the COLREGS, when the own ship is the overtaking vessel, it should give way to the overtaken vessel. Under the provisions of Rule 14, when two ships are in a head-on situation, the two ships should turn right. After the simulation, the system recommends a right turning route. This route not only avoids the PAD of the overtaken vessel, it also avoids the PAD of the head-on vessel. Furthermore, after about 100 min, the own ship safely overtakes the target ship with a distance equivalent to the assigned DCPA value (Fig. 12).

7.3. Case III (multi-target encounter situation)

In this case, when simulating a multi-target encounter situation in narrow waters, the system recommend that, as the navigation environment contains multiple static obstacles and dynamic obstacles, the routes must be able to avoid these obstacles. The own ship has a course of 067° and a speed of 15 knots. The target ship's data is tabulated in Table 3. Fig. 13 shows the navigation situation. If the own ship maintains the original course and speed while no action is taken, then the TCPA with target A will be 11 min and the DCPA will be 0.1 nautical miles. Therefore, there will be risks of a navigation collision (Fig. 14). Moreover, the own ship also has

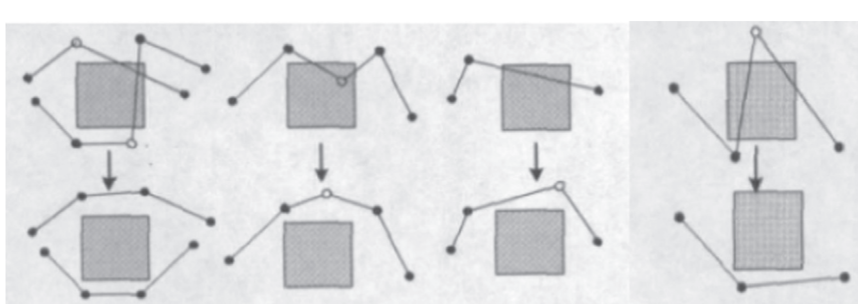

Fig. 5. Genetic operations for route nodes.

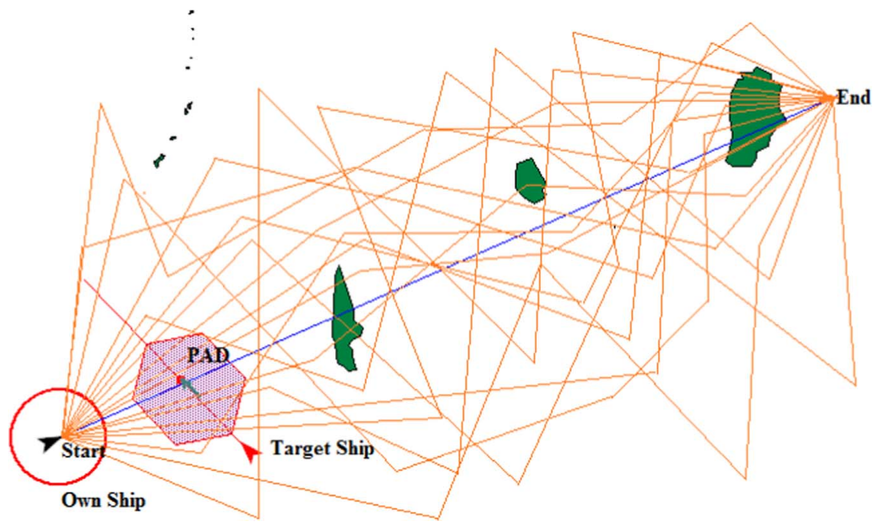

Fig. 6. Case I – candidate routes generated randomly by evolutionary computation without GIS preprocessing. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

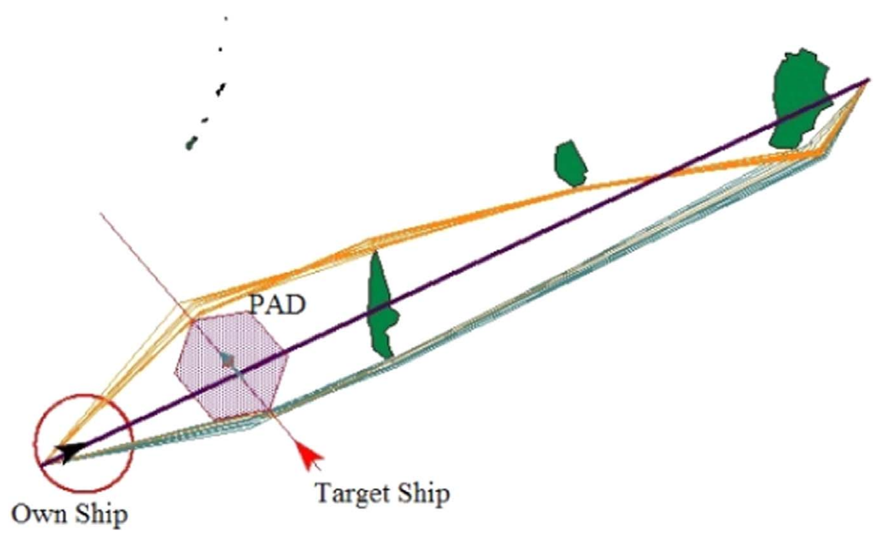

Fig. 7. Case I – original path (with GIS pre-processing). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

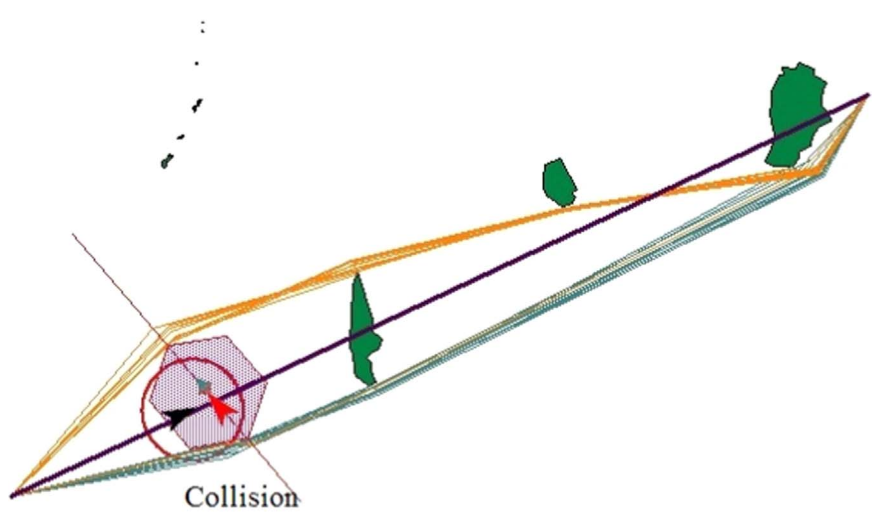

Fig. 8. Case I – collision occurring on the original path after 22 min in the simulation. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

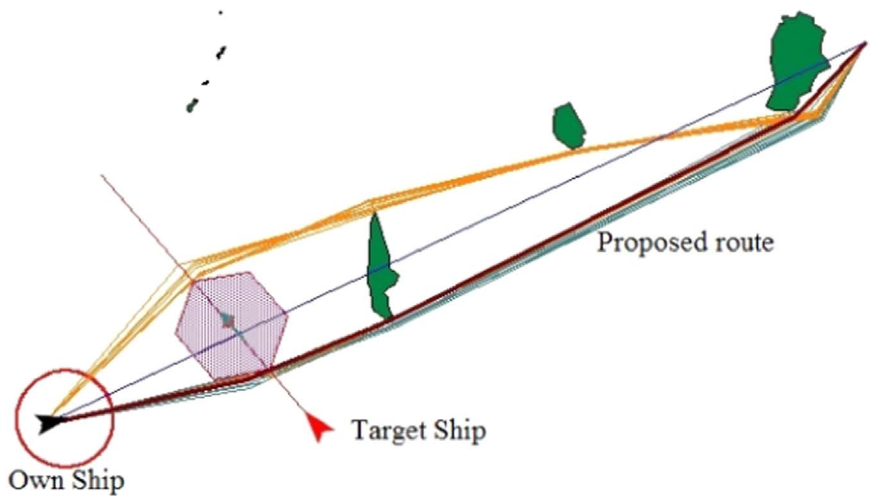

Fig. 9. Case I – proposed route after the simulation. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

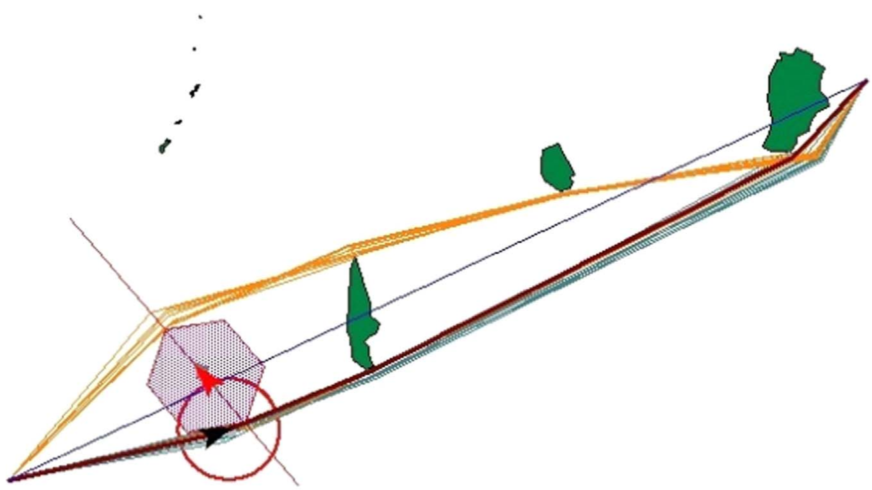

Fig. 10. Case I – proposed route after 24 min in the simulation. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 2
Case III – target ship's data for the head-on and overtaking situation.

Target	Course (°)	Speed (kts)	Bearing (°)	Distance (′)	DCPA (′)	TCPA (min)
A (overtaken)	288	6	288	5.6	0	112
B (head-on)	104	8	287	16.5	0.2	56

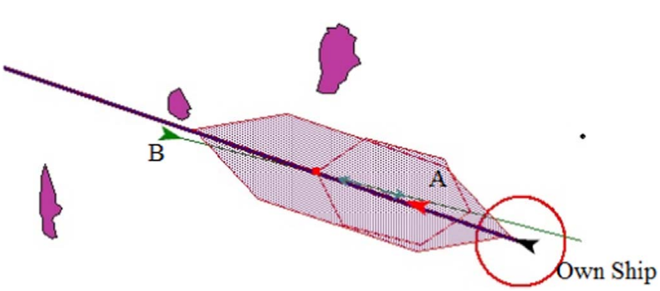

Fig. 11. Case II – original path. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

collision risks because of its close distance to the stand-on vessels of target B and target C. After the simulation, according to the PAD generated, we can immediately determine which ships should be

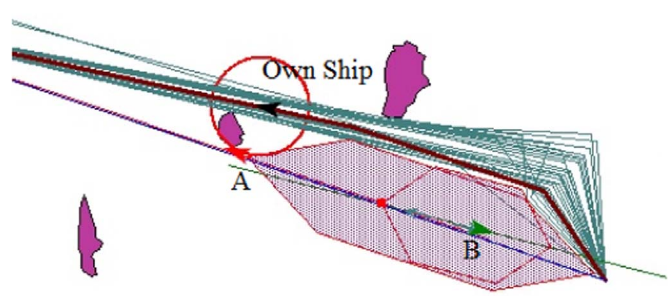

Fig. 12. Case II – proposed route after 100 min in the simulation. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 3
Target ship's data for the multi-target collision avoidance situation.

Target	Course (°)	Speed (kts)	Bearing (°)	Distance (′)	DCPA (′)	TCPA (min)
A	324	10	098	3.7	0.1	11
B	345	8	087	8.8	1.5	32
C	293	12	089	28.7	0.9	69
D	191	18	033	17.1	1.0	35

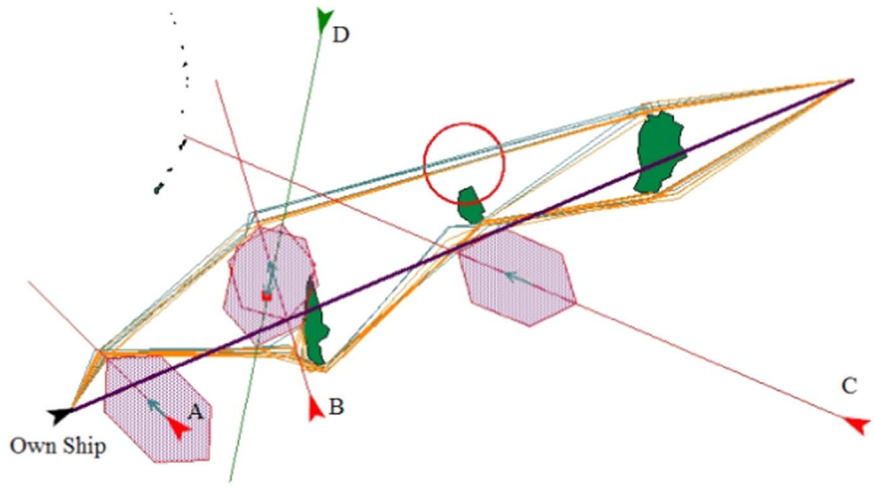

Fig. 13. Case III – original path. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

the top priority to give way to. Since the relative bearing of target A is larger and the distance is short, in order to avoid the inconvenience of large-angle right turning within a close distance, the system recommends adopting a slightly left-turning route, and after 12 min (Fig. 15) and after 42 min (Fig. 16), the own ship can safely pass by target A and target B, respectively, with a range equivalent to the assigned DCPA value, while there are absolutely no safety concerns for target C and target D.

7.4. Verification of candidate routes generated through GIS pre-processing

Taking Case I as an example, Fig. 17 shows a trend diagram comparing the fitness value evolutions of the routes in the generation process using GIS pre-processing and the routes generated randomly without GIS pre-processing. We conducted the simulations on a PC with specifications of Intel Core i5-5200u 2.2 GHz processor, 8 G memory, and Windows 8 operating system. For the computation under GIS pre-processing could be completed in approximately 2–4 s, while it takes about 5–8 s for random search without GIS pre-processing, it takes. From the experiment above, we can see that after combining the GIS initialization processing, candidate routes with better quality can be generated. Although not all the routes generated are necessarily good, every path is a feasible route. If adopting the random search, many infeasible routes will be mixed in the simulation outcomes; therefore, processing speed and the quality of convergence are reduced. Generally, although the study must go through an extra processing of the GIS to generate the candidate routes, the overall execution efficiency is considered to be improved.

8. Conclusions

This study presented a system framework for a navigation decision-support platform that uses the received data of the AIS as a dynamic information source for ships and uses the ECDIS for information archival and processing analysis, in order to expand the roles that the AIS and ECDIS can play in collision-avoidance navigation decision-making. Under this framework, the real-time information about ships in the AIS is transformed into the TCPA, DCPA, and PAD information needed for collision avoidance, in which lags in target ships information processing are prevented. It also extends the PAD beyond the ARPA as a new application of the ECDIS. With the GIS function modules inside ECDIS, preliminary processing and analysis of obstacle avoidance are conducted to generate high-quality initial routes, so that the subsequent selection navigation module using evolutionary computation as a basis has a better set of initial routes and more efficiently generates recommended route. This recommended route simultaneously

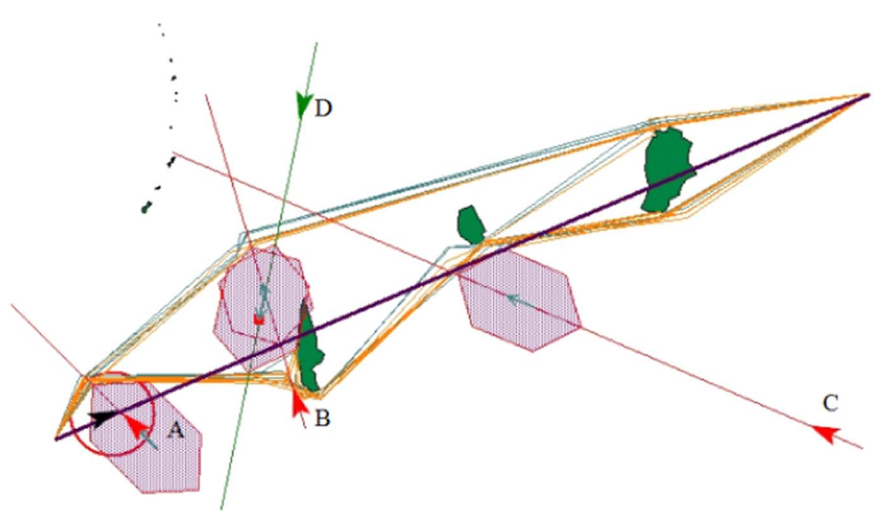

Fig. 14. Case III – original paths after 11 min in the simulation. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

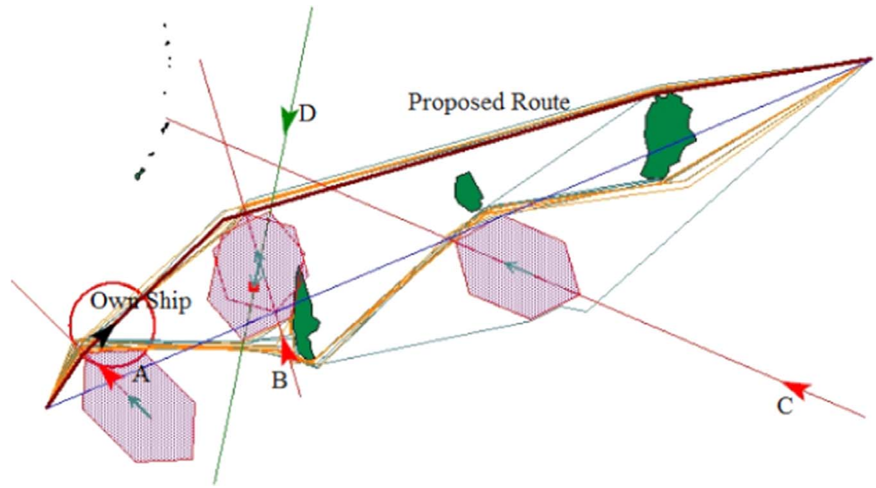

Fig. 15. Case III – proposed route after 12 min in the simulation. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

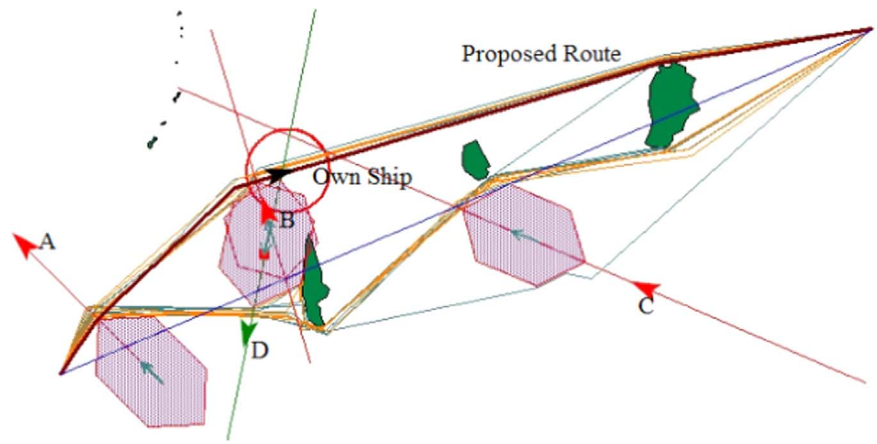

Fig. 16. Case III – proposed route after 42 min in the simulation. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

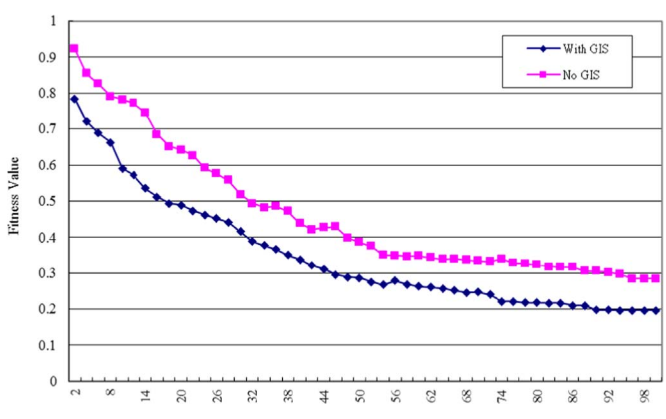

Fig. 17. Evolutionary computation fitness value evolution comparison between GIS pre-processing and no GIS pre-processing.

takes into account collision avoidances with both dynamic targets and static targets. It can be applied on open seas and in narrow waters. Furthermore, since the COLREGS knowledge is also considered in the process of operations as guidance for route planning to comply with the general regulations of navigation, the proposed system can be used as a reference for the ECDIS in developing a collision-avoidance module of the future. However, the current study considers only a single objective, which is to achieve the shortest total distance. However, the maritime navigation situation is complex; the shortest route is not necessarily the best route, since we must take into consideration the weather, sea conditions, man-made obstacles (such as pirates and the restricted navigation zone), and other restrictions. We plan our objectives of subsequent studies to be more diverse. Moreover, rationalization and diversification for a PAD (such as dynamic typhoons, rather than being restricted to ships) also are the aspects that must be further improved in the future, so that the entire system not only can be applied on short-distance collision avoidance but also has the potential to be applied on mid-distance voyage planning and weather routing across the ocean.

Though the so-called decision support system provides recommendations to decision-makers, the paths provided by this system are not necessarily the shortest in theory. Maritime traffic conditions change rapidly, and the OOW should still base their decisions on the conditions at the moment, refer to the recommendations of the system, and then make the best navigational decision according to their own professional judgment.

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